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ScienceDirect

Procedia Engineering 87 (2014) 164 – 167

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

Flexible force sensor based on c-axis oriented aluminum nitride

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Abstract

Force sensors are key components in a wide range of high-controlled environments and operations. Force sensors based on piezoelectric transduction mechanism are particular attractive since they are able to provide electrical signals even without power supply. Among the most investigated materials for force sensing, aluminum nitride (AlN) has the peculiar properties of high isolation and the highest thermal conductivity. Despite the piezoelectric coefficient d_{33} is moderate, AlN thin films integrated on polymeric substrates improve the piezoelectric response of the sensor as a whole. This work presents a promising technology based on piezoelectric highly c-axis oriented aluminum nitride integrated on Kapton substrate, which provides a self-induced three-dimensional structure dome shaped. The flexible piezoelectric transducers realized by this technology detect normal contact forces in the load range of interest for robotics application, with an improvement of the output voltages with respect to similar sensors based on silicon.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

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Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.609

Keywords: Aluminum Nitride, Kapton, force detection, tactile sensing

1. Introduction

The development of micro systems with smart sensing capabilities is paving the way to progresses in technology of humanoid robotics. Indeed humanoids are required to perform tasks closely and safely both with humans and real-world objects. As a consequence, the sensory system of humanoids should be bio inspired and as powerful and performing as the human one. Unlike other senses, sensation of touch is a critical component that plays a fundamental role in the dexterous manipulation capability and in the evaluation of objects properties such as type of material, shape, texture, stiffness, which is not easily possible by vision alone. Understanding of unstructured environments is made possible by touch thorugh the determination of stress distribution in the surrounding area of physical contact; to this aim, in the past two decades, a large number of approaches to tactile sensing and pressure detection have been developed. They are usually based on the conversion of applied forces in a material strain and, consequently, in electric signal by several transduction mechanisms: capacitive, piezoresistive, optical, magneto-inductive, triboelectric and piezoelectric.

By the observation of human tactile abilities and of skin in natural systems, it is clear that an artificial electronic skin should be lightweight, flexible, soft and even wearable. Furthermore, it should be fabricated with compliant materials. Many adopted solutions [1–3] are unsuitable for body parts, such as fingertips, where a high sensors density and minimum spatial resolution of 1 – 2 mm is required. Therefore highly miniaturized systems based on MEMS technology seem to imitate properly the large number of fast responsive mechanoreceptors present in human skin [4,5].

1.1. Transduction mechanisms for tactile sensing

MEMS-based tactile sensors are used in applications where low magnitude contact forces are involved (0.15 – 0.9 N is the force range experienced by humans in normal manipulative tasks). In general, silicon-based diaphragms and cantilevers are realized as sensing structure, while piezoresistive [6,7] and capacitive [8,9] mechanisms are exploited for converting contact forces and pressures into electrical signals. These sensors are able to detect normal pressure in a range of 0 – 130 kPa and shear stress in a range of 0 – 25 kPa. However, capacitive sensors typically require high voltage operation (~100-1000V) and a significant effort on microfabrication, since membranes have to be realized with very small air gaps. Drawbacks of capacitive sensors are related to low reachable resolution, due to the distance between conductive plates, usually greater than the deformation to detect, but also to parasitic capacitances and external electromagnetic fields, which that are source of noise.

Performance of piezoresistive sensors, on the other hand, suffers from signal drift caused by temperature changes. Nevertheless, they offer the advantages of small size, mature technologies and low costs of process, but they are too fragile and require power supply.

Another efficient mechanism exploited for tactile sensing is piezoelectric effect, indeed piezoelectric sensors have been widely studied [10,11] for tactile sensing. They consist of metal electrodes with sandwiched piezoelectric ceramic layer or a piezoelectric polymer. Piezoelectric tactile sensors exhibit high sensitivity with high voltage outputs even with small deformation and they do not require a supply of electrical power, decreasing the power consumption with an important benefit for autonomous robots. In piezoelectric force sensors crucial for the transduction efficiency is the active material; among the available piezoelectric materials one of the most investigated is lead zirconate titanate (PZT) with the highest piezoelectric coefficient (d_{33} = 60pm/V), but with the environmental drawback of Pb presence during synthesis procedures, the requirement of poling treatment for piezoelectricity and the highest dielectric constant. Another interesting material is aluminum nitride (AlN) which has good insulating and dielectric properties but a moderate piezoelectric coefficient d_{33} of 4.7pm/V. AlN-based sensors are able to detect pressure in the range from 0.9 to 400 kPa, showing an excellent linearity and a sensitivity of ~0.9 kPa, which is well within the 10 – 40 kPa range that a human finger applies to sense texture and shapes [10].

In this work we developed a process to fabricate three-dimensional dome-shaped cells that exhibit an enhancement of the AlN piezoelectric coefficient d_{33}. Moreover, the integration of thin piezoelectric film on a flexible substrate by sputtering deposition, increases the generated strain when the force is applied.

2. Flexible sensor fabrication

The conceptual diagram of the process to realize the flexible force transducer is presented in figure 1. A tri-layered sample is fabricated on 25µm thick (DuPont^{TM}) general purpose Kapton substrate laminated on silicon rigid support by 60µm thick silicone adhesive. The fabrication process starts with the sputtering deposition of the first molybdenum (Mo) film (120nm in thickness) that acts as bottom electrode and aluminum nitride (~1µm) film (figure 1(a)). Tactile sensors are shaped in circular 3D-geometry by dry etching using a $SiCl_4$–based plasma (figure 1(b)). AZ5214E positive photoresist is used as photolithographic mask. The Mo bottom common electrode is defined through a wet etching with H_2O_2 solution (30%) as schematically reported in figure 1(c). Sputtering and dry/wet etching parameters are reported elsewhere [12,13]. The last Mo layer (300nm) is then deposited by sputtering and its final shape is defined by lift-off process. A parylene C coating is used as biocompatible protective layer to prevent external damages and to isolate sensor electrically (figure 1(d)). The final design consists of 4 domes with a radius of 300 µm, positioned in a cross-layout design, as showed in figure 2(a).

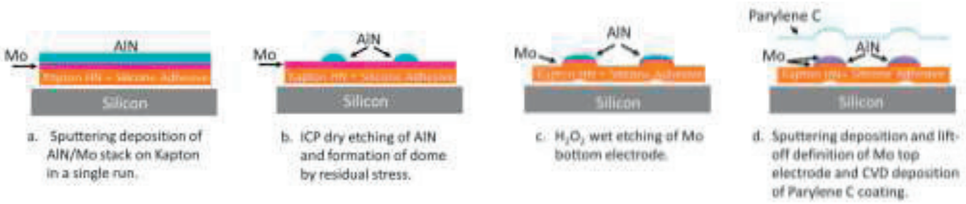

Fig. 1. Steps of fabrication process of force transducer.

2.1. Dome-shaped cells

Fabrication of three dimensional dome-shape cells has been realized exploiting a natural lifting-up of tri-layered Mo/AlN/Mo structure. This effect is due to the compressive residual stress of the AlN over the polymer substrate. It has been estimated by calculating the curvature radius of deflected membrane, after measuring the height of dome by scanning profilometer, and by applying the Stoney equation. The estimated compressive residual stress amounts to –48.1 ± 0.5 MPa [16]. By scanning profilometer, shown in figure 2(b), it is possible to observe that the partial release of residual stress of the AlN crystal on Mo/kapton/adhesive layers is responsible for the dome shape and for a resultant 3D cell whose height reaches a maximum value of ~11 µm in the center.

a b

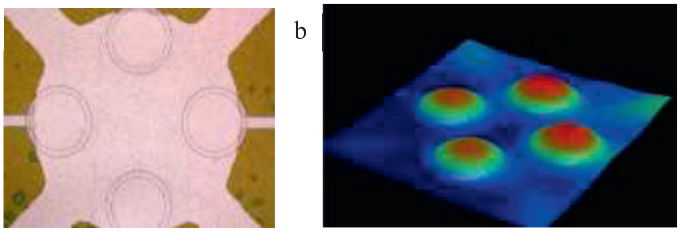

Fig. 2. (a) optical microscope picture of crossed-layout domes; (b) topography of sensing region

In order to investigate the sensing performances of force transducer, the relationship between the applied normal force and generated output voltage has been experimentally estimated. XYZ TEC Push&Pull system has been used both to apply and measure the external contact force in a loading range from 0.002 to 0.05N. The peak output voltage has been measured as a function of the applied force trough a low noise voltage amplifier connected via bluetooth to PC station. Figure 3 shows the results according to various contact force applications (a) and a schematic diagram of the measurement setup. As shown in the graph, all fabricated domes exhibit the same output voltage trend between 2 to 50mN and the voltage changes linearly with force. No deviation from linearity is observed in the range of interest. The piezoelectric coefficient has been estimated from voltage/force response and it amounts to 6.175 ± 0.3842 pm/V.

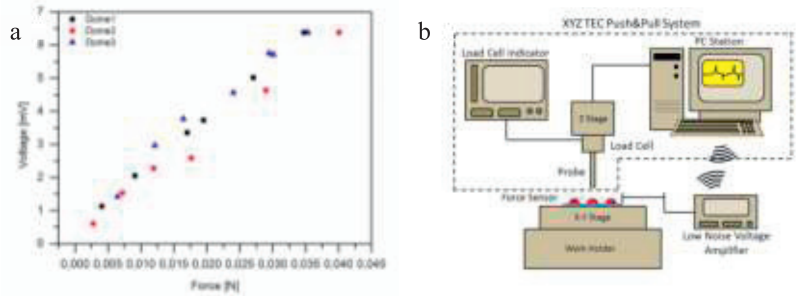

Fig. 3. (a) voltage response of a single dome cell as a function of a normal applied load; (b) schematic diagram of experimental setup.

3. Conclusions

In this work, a fabrication method to realize dome shaped piezoelectric transducer is successfully developed. C-axis oriented AlN thin films, patterned in circular shapes, release a compressive stress that is the origin of the three dimensional domes on the flexible substrate of Kapton. The application of dome shaped cell (even if fixed on a rigid support) instead of conventional flat diaphragms improves the piezoelectric coefficient of about 40% in comparison to standard aluminum nitride on silicon transducers.

Acknowledgements

The authors would like to acknowledge STMicroelectronics for technical support and availability. This research is funded by the project PON ITEM.

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